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Search for resonant top quark plus jet production in $t\bar{t}$ + jets events with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV

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This paper presents a search for a new heavy particle produced in association with a top or antitop quark. Two models in which the new heavy particle is a color singlet or a color triplet are considered, decaying, respectively, to $\bar{t}q$ or tq, leading to a resonance within the $t\bar{t}$ + jets signature. The full 2011 ATLAS pp collision data set from the LHC (4.7 fb^{-1}) is used to search for $t\bar{t}$ events produced in association with jets, in which one of the W bosons from the top quarks decays leptonically and the other decays hadronically. The data are consistent with the Standard Model expectation, and a new particle with mass below 430 Gev for both W' boson and color triplet models is excluded at 95% confidence level, assuming unit right-handed coupling.

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In the past few decades, remarkable agreement has been shown between measurements in particle physics and the predictions of the Standard Model (SM). The top quark sector is one important place to look for deviations from the SM, as the large top quark mass suggests that it may play a special role in electroweak symmetry breaking. The recent top quark forward-backward asymmetry measurements from the Tevatron experiments [1,2] are in marginal agreement with SM expectations. A non-SM explanation could come from a possible top-flavor-violating process [3–5]. In these models, a new heavy particle R would be produced at the LHC in association with a top or antitop quark. Figure 1 shows representative production diagrams for these new particles, for the cases of $R = W'$ or $R = \phi$ (see below). As shown in Ref. [6], the production mechanism in pp collisions mainly involves quarks rather than antiquarks at $\sqrt{s} = 7$ TeV, even for relatively low mass particles.

The larger number of quarks relative to antiquarks produced in the initial state at the LHC leads to a resonance R that decays predominantly to either the t + jet or $\bar{t}$ + jet final state, where baryon number conservation restricts the models that are available. Two models that can give rise to these final states are a color singlet resonance (W') mostly in the $\bar{t}q$ system, and a di-quark color triplet model with a resonance (ϕ) in the tq system. In both cases a $t\bar{t}$ + jet final state is produced, but a peak will be present in only one of the t + jet or $\bar{t}$ + jet invariant mass distributions. The new resonances are assumed not to be self-conjugate, which makes searches for same-sign top quarks insensitive to them [7–9], and to have only right-handed couplings. The t or $\bar{t}$ then decays to W^+b or $W^-\bar{b}$, respectively. This paper considers the decay signature of events in which one W boson decays leptonically (to an electron or muon, plus neutrino final state) and the other W boson decays hadronically. The first direct search for such particles was performed at CDF [10], which excluded color triplet resonances with masses below 200 GeV and W' resonances with masses below 300 GeV, for particles with unit right-handed coupling (g_R) to tq. As is done in this paper, CDF used the formalism in Ref. [3] to define g_R. CMS recently performed a search that excluded a new W' with a mass less than 840 GeV [11] for particles with $g_R = 2$ [12].

The analysis presented here uses the full ATLAS 7 TeV pp collision data set collected in 2011, corresponding to 4.7 ± 0.2 fb^{-1} of integrated luminosity [13,14] delivered by the LHC. ATLAS [15] is a multipurpose particle physics detector with cylindrical geometry [16]. The inner detector (ID) system consists of a high-granularity silicon pixel detector and a silicon microstrip detector, as well as a transition radiation straw-tube tracker. The ID is immersed in a 2 T axial magnetic field and provides charged particle tracking in the range $|\eta| < 2.5$. Surrounding the ID, electromagnetic calorimetry is provided by barrel and endcap liquid-argon (LAr)/lead accordion calorimeters and LAr/copper sampling calorimeters in the forward region. Hadronic calorimetry is provided in the barrel by a steel/scintillator tile sampling calorimeter, and in the endcaps and forward region by LAr/copper and LAr/tungsten sampling calorimeters, respectively. The muon spectrometer comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field with a bending power of 2–8 Tm, generated by three superconducting air-core toroid systems. A three-level trigger system is used to select interesting events. The level-1 trigger is implemented in hardware and uses a subset of detector information to reduce the event rate to a design value of at most 75 kHz. This is followed by two

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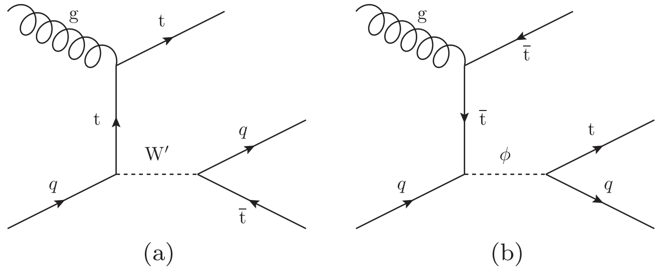


FIG. 1. Example production and decay Feynman diagrams for the (a) W' and (b) ϕ models.

software-based trigger levels, level-2 and the event filter, which together reduce the event rate to ~300 Hz.

Events with an electron (muon) are required to have passed an electron (muon) trigger with a threshold of transverse energy $E_T > 20$ GeV (transverse momentum $p_T > 18$ GeV), ensuring that the trigger is fully efficient for the offline selection discussed below. Electrons reconstructed offline are required to have a shower shape in the electromagnetic calorimeter consistent with expectation, as well as a good quality track pointing to the cluster in the calorimeter. Candidate electrons with $E_T > 25$ GeV are required to pass the "tight" electron quality criteria [17], to fall inside a well-instrumented region of the detector ($|\eta| < 2.47$, excluding $1.37 < |\eta| < 1.52$), and to be isolated from other objects in the event. Muons with transverse momentum $p_T > 20$ GeV are required to pass muon quality criteria [18], to be well measured in both the ID and the muon spectrometer, to fall within $|\eta| < 2.5$, and to be isolated from other objects in the event.

Jets are reconstructed in the calorimeter using the anti-k_t [19] algorithm with a radius parameter of 0.4. Jets are required to satisfy $p_T > 25$ GeV and $|\eta| < 2.5$. Events with jets arising from electronic noise bursts and beam backgrounds are rejected [20]. Jets are calibrated to the hadronic energy scale using p_T- and η-dependent corrections derived from simulation, as well as from test-beam and collision data [21]. Jets from the decay of heavy flavor hadrons are selected by a multivariate b-tagging algorithm [22] at an operating point with 70% efficiency for b jets and a mistag rate for light quark jets of less than 1% in simulated $t\bar{t}$ events. Neutrinos are inferred from the magnitude of the missing transverse momentum (E_T^{miss}) in the event [23].

The signal region for this analysis is defined by requiring exactly one charged lepton and five or more jets, including at least one b-tagged jet. To select events with a leptonically decaying W boson, events are required to have $E_T^{\text{miss}} > 30$ GeV ($E_T^{\text{miss}} > 20$ GeV) in the electron (muon) channel. Additionally, the event must have a transverse mass of the leptonically decaying W boson $m_T^W > 30$ GeV in the electron channel, or scalar sum $E_T^{\text{miss}} + m_T^W > 60$ GeV in the muon channel [24]. Here, $(m_T^W)^2 = 2E_T^{\text{miss}}E_T^{\ell}(1 - \cos\phi)$, where E_T^{ℓ} is the magnitude of the transverse momentum of the lepton, and ϕ is the angle between the lepton and the missing transverse momentum in the event.

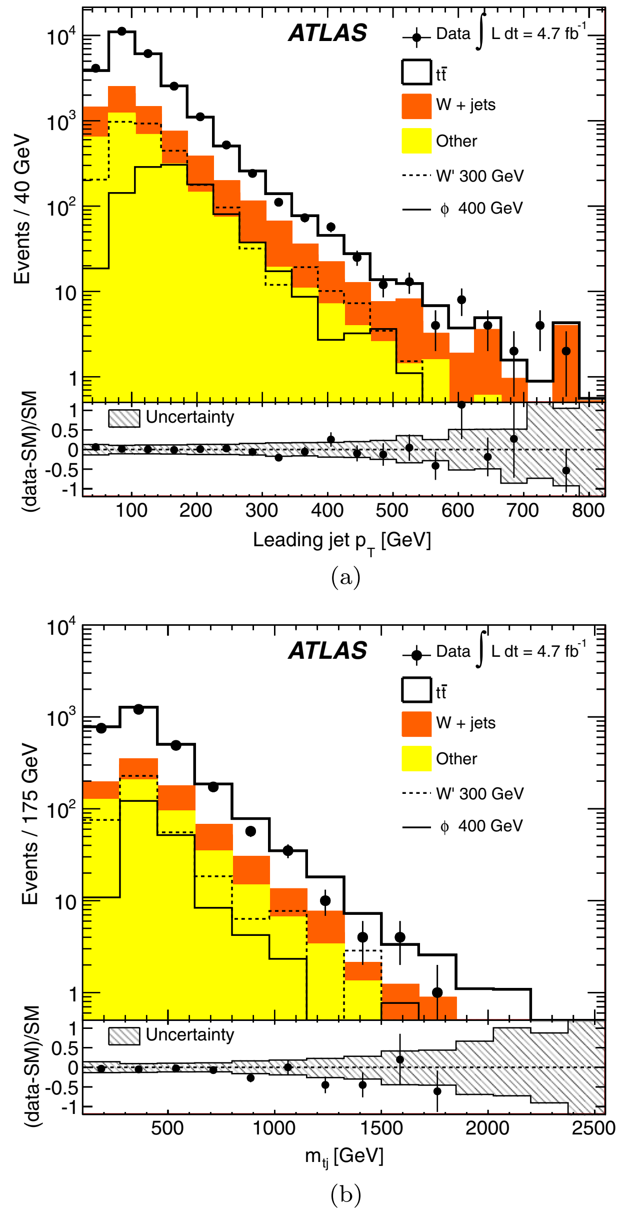


FIG. 2 (color online). The leading jet p_T in the four-jet $t\bar{t}$ control region (a), and m_{tj} in the five-jet $t\bar{t}$ control region (b). The example signal-only distributions are overlaid for comparison, where unit coupling for the new physics process is assumed. The total uncertainty shown on the ratio includes both statistical and systematic effects. The "other" background category includes single top production, diboson production, and multijet events.

A variety of Monte Carlo generators are used to study and estimate backgrounds. The generated events are processed through full detector simulation [25], based on GEANT4 [26], and include the effect of multiple pp interactions per bunch crossing. To predict the event yield, the simulation is given an event-by-event weight such that the distribution of the number of pp collisions matches that in data.

The $t\bar{t}$ background is modeled with MC@NLO v4.01 [27] interfaced to HERWIG v6.520 [28] and JIMMY v4.31 [29]. An additional $t\bar{t}$ sample modeled with MC@NLO interfaced to PYTHIA v6.425 [30] is used to study potential systematic uncertainties. Other $t\bar{t}$ samples use POWHEG [31] interfaced either to PYTHIA or HERWIG, as well as AcerMC v3.8 [32]. The background from the production of single W bosons in association with extra jets is modeled by the ALPGEN v2.13 [33] generator interfaced to HERWIG. The MLM matching scheme [34] is used to form inclusive W boson + jets samples such that overlapping events produced in both the hard scatter and parton showering are removed. In addition, the heavy flavor contributions are reweighted using the data-driven procedures of Ref. [24] using the full 2011 LHC data set. Diboson events are generated using HERWIG. Single-top-quark events are modeled by MC@NLO, interfaced with HERWIG for the parton showering, in the s channel and Wt channel, and by AcerMC v3.8 in the t channel. The small background in which multijet processes are misidentified as prompt leptons is modeled from a data-driven matrix method [35]. In determining the expected event yields, the $t\bar{t}$ cross section is normalized to approximate next-to-next-to-leading-order QCD calculations of 167^{+17}_{-18} pb for a top quark mass of 172.5 GeV [36,37], and the total W + jets background is normalized to inclusive next-to-next-to-leading-order predictions [38]. Signal events are produced, for a range of W' and ϕ masses, with MadGraph v5.1.3.16 [39] and interfaced to PYTHIA v6.425. Next-to-leading-order (NLO) cross sections are used for the predicted W' boson signal normalization [6], and leading-order (LO) cross sections using MSTW2008 are used for the ϕ-resonance normalization [3].

Events are reconstructed with a kinematic fitting algorithm that utilizes knowledge of the overconstrained $t\bar{t}$ system to assign jets to partons. In the fit, the two top quark masses are each constrained at the particle level to

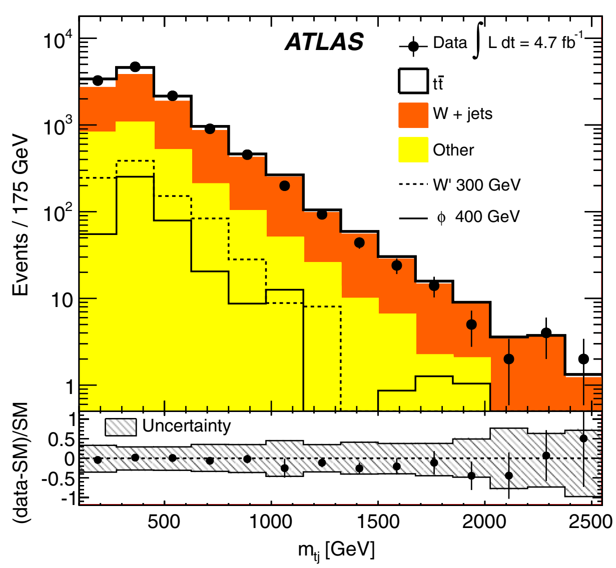


FIG. 3 (color online). Expected and observed distribution of m_{tj} in the $W+$jets control region. The example signal-only distributions are overlaid for comparison, where unit coupling for the new physics process is assumed. The total uncertainty shown on the ratio includes both statistical and systematic effects. The other background category includes single top production, diboson production, and multijet events.

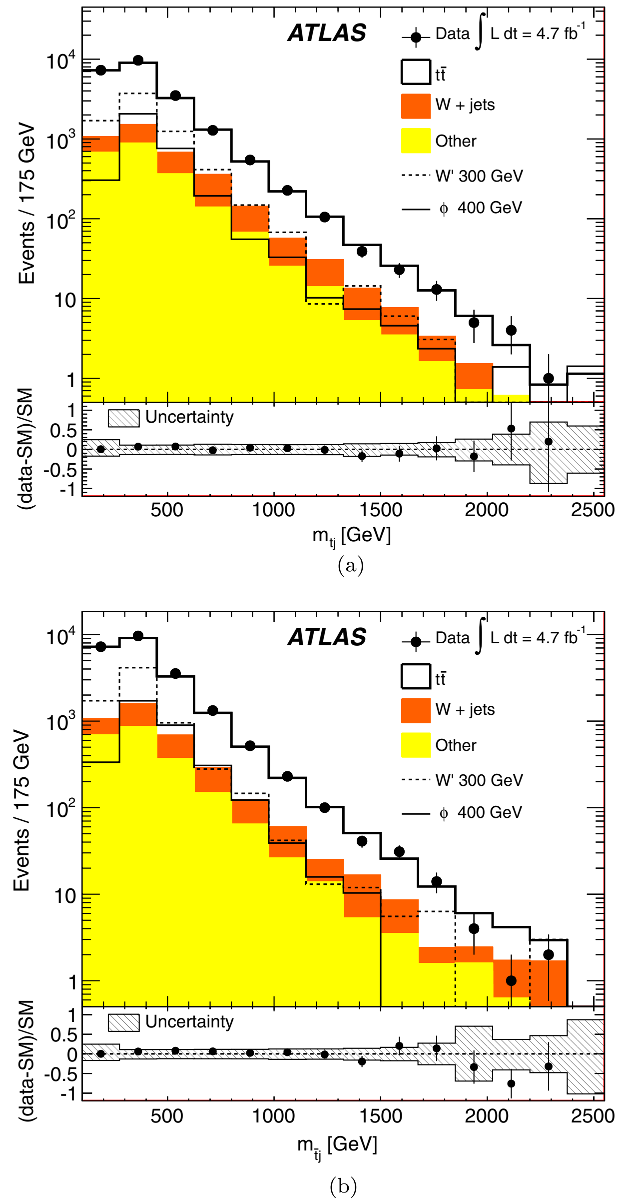


FIG. 4 (color online). Expected and observed distributions of (a) m_{tj} and (b) $m_{\bar{t}j}$ in the signal region. The example signal distributions assume unit coupling for the new physics process. The total uncertainty shown on the ratio includes both statistical and systematic effects. The other background category includes single top production, diboson production, and multijet events.

TABLE I. Expected and observed yields in the four control regions (CR). Total refers to the total expected background, including $t\bar{t}$, W + jets, and the other smaller backgrounds: single top production, diboson production, and multijet events. The last two lines show the expected number of events for two benchmark signal samples in each of these control regions. The errors include all systematic uncertainties.

	Preselection CR	W + jets CR	Four-jet $t\bar{t}$ CR	Five-jet $t\bar{t}$ CR
$t\bar{t}$	50000 ± 4700	2000 ± 400	19000 ± 600	2100 ± 200
W + jets	46000 ± 14000	7000 ± 2900	3800 ± 800	360 ± 170
Total	116000 ± 21000	12000 ± 3600	26000 ± 1300	2900 ± 440
Observed	110933	11858	26197	2736
300 GeV W'	13900 ± 670	930 ± 110	3000 ± 400	400 ± 80
400 GeV ϕ	6100 ± 200	430 ± 60	1100 ± 100	200 ± 20

172.5 GeV by a penalty in the likelihood, computed from variations from this nominal value and the natural top quark width of 1.5 GeV. The two W boson masses are similarly constrained to 80.4 GeV within a width of 2.1 GeV. This allows the z component of the momentum of the neutrino from the leptonically decaying W boson to be computed. Both solutions from the quadratic ambiguity of this computation are tested when computing the likelihood. Charged lepton, neutrino, and jet four-momenta are constrained in the fit by resolution transfer functions derived from simulated $t\bar{t}$ events that relate the measured momenta in the detector to true particle momenta. The full shapes of these transfer functions are used in the likelihood computation. All assignments of any four jets to partons from the $t\bar{t}$ decay are tested and the assignment with the largest likelihood output for the $t\bar{t}$ hypothesis is selected. After the assignment is selected, the originally measured jet and lepton momenta and $E_{\mathrm{T}}^{\mathrm{miss}}$ are used. The remaining jets not associated with the $t\bar{t}$ partons are included to form m_{tj} and $m_{\bar{t}j}$ masses, where the charge of the lepton is used to infer which is the top candidate and which is the antitop candidate. All combinations of extra jets with the top and antitop quark candidates are considered, and the pairings that give the largest m_{tj} and $m_{\bar{t}j}$ masses are used. In this way, the same extra jet can (but does not necessarily have to) be used to form m_{tj} and $m_{\bar{t}j}$. These two masses are used as observables for the search.

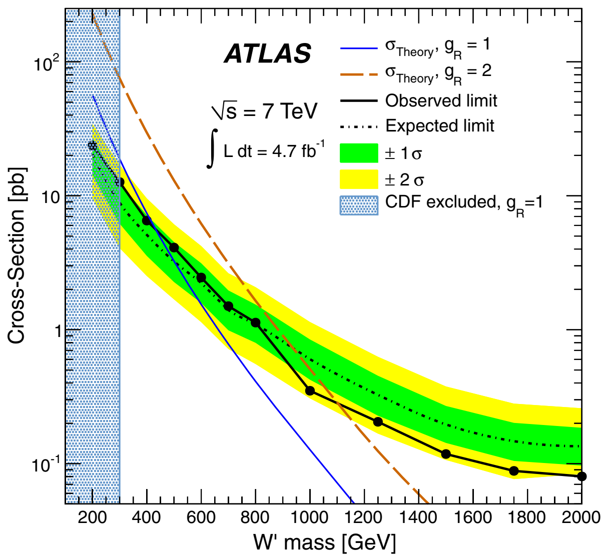
Several control regions are used to ensure good modeling and understanding of the backgrounds before the signal region is examined. The preselection control region requires at least four jets, but does not require a b tag. The dominant $t\bar{t}$ background is tested in a control region with exactly four jets (including at least one b-tagged jet). The rejection of events with more than four jets reduces signal contamination. A second $t\bar{t}$ control region is defined by events with exactly four jets with p_{T} above 25 GeV, one of which must be b tagged, and exactly one additional jet with p_{T} between 20 GeV and 25 GeV. Signal contamination is further reduced by requiring that the $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ between the fifth jet and both the reconstructed top and antitop quarks is greater than $\pi/2$. Figure 2 shows distributions in the two $t\bar{t}$ control regions, where good agreement is observed between data and the prediction. The second major background, production of single W bosons in association with extra jets, is tested in a

TABLE II. Expected and observed yields in different signal regions. The errors include all systematic uncertainties. Total refers to the total expected background, including $t\bar{t}$, W + jets, and the other smaller backgrounds: single top production, diboson production, and multijet events, which are not tabulated separately here. Signal window eff. refers to the efficiency for the signal to fall inside the optimized two-dimensional mass window. The signal region yield is calculated in the mass window at each benchmark signal point. Signal σ refers to the total expected signal cross section, not taking into account the t (or $\bar{t}$) plus jet branching fraction.

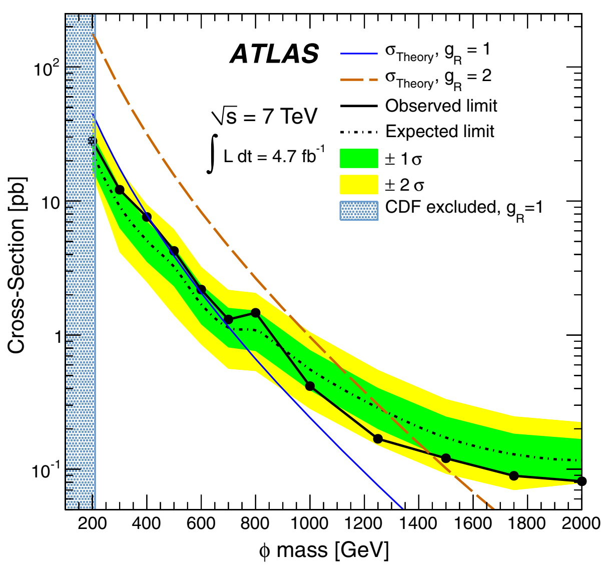
	Entire signal region	300 GeV W'	600 Gev W'	400 GeV ϕ	800 GeV ϕ
m_{tj} window [GeV]		$344 < m_{tj} < 494$	$566 < m_{tj} < 904$	$401 < m_{tj} < 455$	$766 < m_{tj} < 819$
$m_{\bar{t}j}$ window [GeV]		$292 < m_{\bar{t}j} < 339$	$549 < m_{\bar{t}j} < 650$	$371 < m_{\bar{t}j} < 608$	$628 < m_{\bar{t}j} < 973$
Signal window eff.		7.5%	9.9%	11.9%	5.7%
$t\bar{t}$	18000 ± 3000	740 ± 160	270 ± 60	660 ± 150	60 ± 10
W + jets	1700 ± 560	60 ± 30	30 ± 20	80 ± 40	8 ± 5
Total	22000 ± 3700	820 ± 190	320 ± 80	780 ± 180	70 ± 20
Observed	22731	970	343	923	77
Signal region yield		560 ± 120	98 ± 24	410 ± 100	20 ± 6
Signal σ		19.0 pb	1.55 pb	7.9 pb	0.67 pb

control region with five or more jets, vetoing events with b-tagged jets. The requirement of zero b-tagged jets reduces both signal and $t\bar{t}$ contamination. The distribution in Fig. 3 shows good agreement between data and the prediction within uncertainties. Table I summarizes the expected and observed yields in the control regions.

Figure 4 shows the expected and observed m_{tj} and $m_{\bar{t}j}$ distributions in the signal region. The data are found to be consistent with the SM expectation. A variety of potential systematic effects are evaluated for the predicted signal and the background rates and shapes. The dominant systematic effects of the jet energy scale [21] and resolution [40] lead to uncertainties of up to 10% on the total background rate and up to 21% on the total signal expectation, depending on the mass of the new particle. The other dominant systematic uncertainty from the difference in b-tagging efficiency between simulation and data leads to uncertainties of roughly 16% on both the signal and background rates. Effects due to lepton trigger uncertainties and ID efficiency as well as the energy scale and resolution are

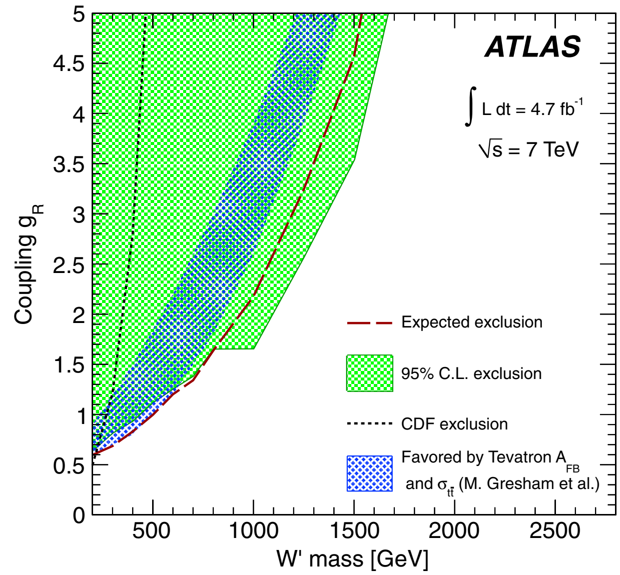


(a)

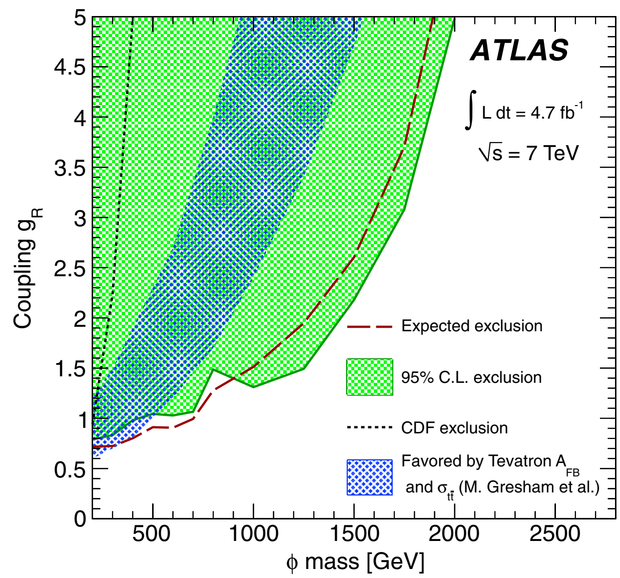


(b)

FIG. 5 (color online). Expected and observed 95% C.L. upper limits on the (a) W' and (b) ϕ model cross sections. The CDF result is documented in Ref. [10]. The W' cross sections are NLO calculations, and the ϕ cross sections are LO calculations.



(a)



(b)

FIG. 6 (color online). Expected and observed 95% C.L. upper limits on the (a) W' and (b) ϕ model cross sections assuming a cross section that scales with g_R^2. The hatched area shows the region of parameter space excluded by this search at 95% C.L. The CDF result is documented in Ref. [10]. The W' cross sections are NLO calculations, and the ϕ cross sections are LO calculations. The region favored by the Tevatron A_{FB} and $\sigma_{t\bar{t}}$ measurements is shown as the dark band [42].

assessed using $Z \to ee$ and $Z \to \mu\mu$ data, which lead to systematic uncertainties of a few percent. Other potential systematic effects considered are the size of the small multijet background (assigned 100% uncertainty); $t\bar{t}$ generator uncertainties (evaluated by comparing different results using the MC@NLO and POWHEG generators, 1–10%); $t\bar{t}$ showering and fragmentation uncertainties (evaluated by comparing samples using both PYTHIA and HERWIG, 1%–6%); an uncertainty on the total integrated luminosity (3.9%) [13,14]; and the amount of QCD radiation for the signal and the $t\bar{t}$ background (approximately 10%, evaluated using AcerMC). Total cross section uncertainties of 10% (55%) are used for the $t\bar{t}$ (W + jets) backgrounds.

Expected and observed upper limits on the signal cross section are computed at discrete mass points as follows. For each benchmark signal mass point under consideration, a signal region is defined in the m_{tj}-$m_{\bar{t}j}$ plane. When setting limits for the W' (ϕ) model, the m_{tj} ($m_{\bar{t}j}$) window is significantly wider than the $m_{\bar{t}j}$ (m_{tj}) window to account for the fact that the resonance is predominantly in the $m_{\bar{t}j}$ (m_{tj}) system. The windows are optimized to maximize sensitivity, accounting for the full effect of systematic uncertainties. Typical mass windows are shown in Table II. For each mass window, 95% confidence level (C.L.) upper limits on the signal cross section (times the branching ratio to t or $\bar{t}$) are computed using a single bin frequentist CL_s method [41]. No shape information is used within the mass windows. Table II shows the expected and observed event yields in several of the signal region windows. Expected and observed 95% C.L. lower limits on the signal mass are derived, assuming a coupling of $g_R = 1$ and $g_R = 2$, and are shown in Fig. 5. Assuming that the cross section scales as g_R^2, the exclusion in the mass-coupling plane is shown in Fig. 6. As shown, most of the parameter space in this model, which was favored by the Tevatron forward-backward asymmetry and cross section measurements [42], has been excluded.

In conclusion, this paper presents a search for a new heavy particle R in the tj or $\bar{t}j$ system of $t\bar{t}$ plus extra jet events with the ATLAS detector. Such new particles have been proposed as a potential explanation of the difference from the SM values of the forward-backward asymmetries measured in top quark pair production at the Tevatron. The full 2011 ATLAS pp data set (4.7 fb^{-1}) is used in the search. Assuming unit coupling, the expected 95% C.L. lower limit on the mass of the new particle is 500 (700) GeV in the W' (ϕ) model. No significant excess of data above SM expectation is observed, and 95% C.L. lower limits of 430 GeV for both the W' and ϕ models are set. At $g_R = 2$, the limits are 1.10 (1.45) TeV for the W' (ϕ) model, with expected limits of 0.93 (1.30) TeV. These are the most stringent limits to date on such models. Most of the regions of parameter space for these models that are more consistent with the Tevatron forward-backward asymmetry and $t\bar{t}$ cross section measurements than the SM are excluded at 95% C.L. by these results.

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